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Development of a Hybrid Active-Passive Solar Tracker Using GPS Tracking and Image Processing

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Abstract

In the presented work, the authors propose an innovative hybrid system of an active-passive solar tracker using GPS tracking by employingSG2 algorithm, which is a fast implementation of the popular Solar Position Algorithm (SPA), combined with active tracking using image processing algorithms and a commercial webcam as the sensing element. The analysis of acquired images with a web camera allows accurate extraction of information about the position of the sun with respect to both elevation and azimuth.

The main advantage of this system is its high flexibility to work in extreme conditions when the position of the sun is not very clear due to weather conditions such as cloud cover. The system has the ability to track the sun in both real-time that is independent of the spatiotemporal coordinates of the location, and passively which is dependent on the spatiotemporal coordinates of the location.

The information extracted from the cam-GPS system is used to control the two servo motors, one each for the azimuth and altitude axis of the dual mechanism of the solar tracker to realize the optimal alignment of the payloads attached with the solar tracker with the objective of increasing the power generation.

Keywords: *Solar Tracker; GPS Tracking; Solar Position Algorithm; Image Processing.*

1. INTRODUCTION

The sun produces a massive amount of energy by the process of nuclear fusion, approximately 48% of which is absorbed by the earth's surface, which is sufficient to meet the early world energy needs (Emilio *et al.* 2012; Hinshaw *et al.* 2009). However, the density of sunlight is lower than other resources of energy resulting in lower utilization efficiency, making it inevitable to include high initial costs and installation areas. There are two components of sunlight; direct beam carrying over 90% of solar energy and diffuse sunlight, the blue sky on a bright sunny day, and almost total on a cloudy day (Ayoub, 2012). Thus, it is of utmost importance to utilize this direct beam to get maximum power generation from the solar device in use. This solar energy is supposed to be one of the most favorable and perhaps the fastest growing candidates among renewable energy resources and Environmental friendly. This vital technology is aimed to substitute the expensive and limited fossil fuel resources. The above is done by converting the freely available natural sunlight into clean, usable forms of energy as heat and the most demanded electric energy (Kadmiri *et al.* 2015).

The conversion of the freely available solar energy into usable forms of energy is usually done by solar systems called payloads which are usually photovoltaic cells, Fresnel reflectors, lenses, parabolic reflectors, or the mirrors of a heliostat. Thus, solar trackers are the additional systems whose objective is to orient these solar collector systems automatically. For the flat panel collector systems, the objective is to reduce the angle of incidence and to align the optical axis with the sun's position in concentrator collector systems such as concentrated photovoltaics (CPV) and concentrated solar power (CSP) applications to maximize the energy conversion efficiency(Armstrong and Hurley, 2010; Calabrò, 2014). Hence, the solar concentrators systems in conjunction with solar tracker systems make it feasible to increase the solar energy density

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with the result as a decrease in installation area and a general improvement in the solar conversion efficiency of about 30–40% with respect to the stationary systems (Huang *et al.* 2011; Masters, 2013; Mousazadeh *et al.* 2009).

There are numerous common aspects of sun trackers. Commonly, they are classified into two broad categories as passive and active trackers. Passive trackers are the ones that mainly depend on the principles of imbalance such as the thermal expansion of matter or methods that use pre-stored data, while active trackers are based on electronic devices and may use microprocessors and sensors, date and time-based algorithms, or a combination of both to detect the position of the sun. Another way to distinguish between sun-tracking systems is on the basis of their mechanical system's degrees of freedom. The trackers having a single degree of freedom are called horizontal/vertical/tilted single-axis trackers (HSAT/VSAT/TSAT).On the other hand, dual-axis trackers have two degrees of freedom, mainly the tip-tilt/altitude-azimuth dual-axis solar trackers (TTDAT/AADAT), making them more efficient(Kadmiri *et al.* 2015).

Numerous research studies in this context have been conducted using different methodologies, techniques, advanced measurement to improve the above efficiency and simultaneously decreasing the cost to produce each watt of energy. The trackers developed mostly involves the application of discrete elements as sensors like light-dependent resistors (LDRs) or photodiodes to approximate the position of the sun (Davies 1993; Lynch and Salameh 1990) as shown in Fig. 1.

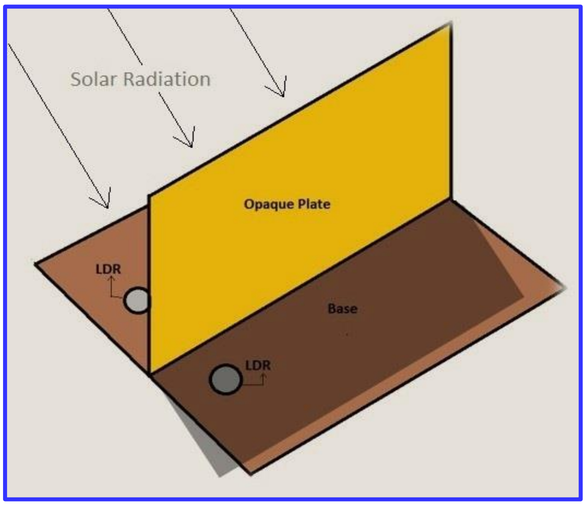

Fig. 1: Normal operating principle of light-dependent sensors

The biggest drawback of using these types of sensors is their high sensitivity towards extreme weather conditions such as temperature, humidity, and cloud cover (Hession *et al.* 1984). To overcome the above drawback, there have been developments that exhibit better performance and accuracy but which depend on sophisticated control systems and complex electronic circuitry (Roth *et al.* 2004) and involving high installation and maintenance costs (Bahgat *et al.* 2005).

Thus, this work is aimed at developing a solar tracking system that combines the abilities of active and passive solar tracking systems by finding an appropriate tradeoff between the two methodologies. The passive features of the system are accomplished by using a sun tracking algorithm SG2 (Blanc and Wald, 2012) which is an approximation of the original Solar Position Algorithm (Reda and Andreas, 2008) but with faster implementation in which the input acquisition is made by using a GPS module. On the other hand, the active features are included with the use of machine/computer vision by using alow-cost webcam as a sensing element. Image processing algorithms are employed in the negative feedback closed control loop system to track the sun actively. It is worth mentioning here that since most of the solar tracking units employ a computer to track, monitor, and register information, it is very convenient to use the same in this case (Arturo and Alejandro, 2014).

1.1 Fundamentals of operation and details of the technical structure

There are generally two broad motions for the sun with respect to an observer on the earth's surface; one from east-west called the azimuthal motion and the other in reference to the change in the height of the sun known as the altitude motion. Due to the above two motions, there is no stable position in which a solar collecting system can be aligned, making it inevitable to take into consideration two degrees of freedom for motions of the collector system. The objective of this paper is to develop a two-axis solar tracker combining the traits of a passive and active tracker. To achieve this, a feed-forward (open-loop) control system is used in combination with negative feedback (closed-loop) control operating system.

To understand and study the advantages and drawbacks of the proposed solar tracking methodology, an experimental prototype was designed and fabricated. The proposed prototype uses a practical and straightforward approach to make the system align with the sun's direction. The proposed solar tracker concept is comprised of three main modules, namely:

(a) *Data acquisition Unit*: done in two stages, first via a GPS module and second via a webcam.

(b) *Control Unit*: comprising of a computer and Arduino Uno board.
(c) *Mechanical Unit*: the dual axis-turning mechanism consisting of servo motors.

Fig. 2 illustrates the complete architecture of the proposed solar tracker. This dual-axis tracker can achieve 180 degrees of both azimuth and elevation movements. This movement was limited to 180 degrees in this model and can easily be extended to full 360-degree movement by the use of full rotating servo/stepper motors. The first stage of the data acquisition unit is a GPS module (GY-GPS 6MV2) that collects the current date, time, latitude, and longitude of the location. The second stage comprises a commercial plug-play webcam (Quantum QHM495LM), which offers an image resolution of 640 x480 pixels. An X-ray film was used as a polarizing filter in front of the webcam to prevent the saturation of the charge-coupled device (CCD) in conditions of unusually intense solar radiation. This filter was useful to prepare a real-time pre-binarization of the acquired images to speed up the process of active tracking of the sun, see Fig. 3. The control unit comprises a personal computer to which the webcam and an Arduino Uno board were connected through USB ports. The GPS module was connected to the Arduino Uno to facilitate the collection of spatiotemporal data. The mechanical unit comprises two servo motors, one each for the azimuth and altitude movements, connected to the Arduino Uno board. The entire processing of the algorithm is done in MATLAB, which uses the Arduino Uno board as a microprocessor unit to control the servo motors.

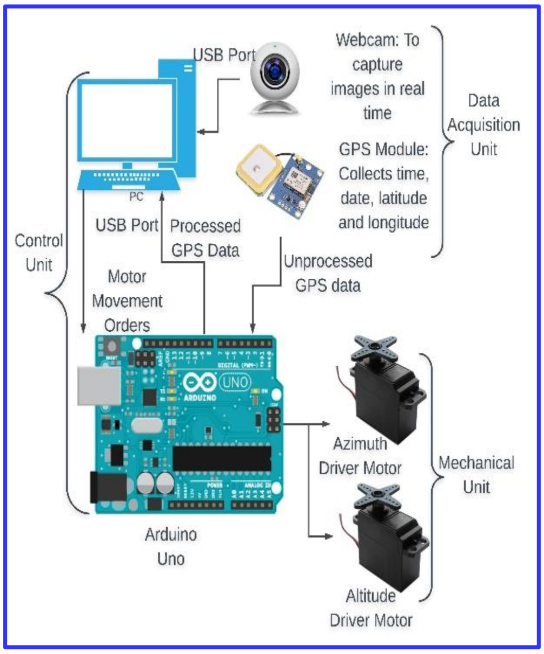

Fig. 2: Complete architecture of the proposed solar tracker

Fig. 3: Real-time pre-binarization of the captured image

2. METHODOLOGY USED TO TRACK THE SUN

A reference point is required by a controller to provide a desired stage or position to be established, which is dependent on the exterior conditions. This is done by employing a sun tracking algorithm SG2 (Blanc and Wald, 2012) which is a fast approximation of the original Solar Position Algorithm (Reda and Andreas, 2008). The control unit calculates the azimuth and altitude positions of the sun using the SG2 algorithm with the inputs like date, time, latitude, and longitude collected by the GPS module. If the GPS module is not able to receive valid GPS data, then predefined values of latitude and longitude, date, and time from the computer system are taken as input to the SG2 algorithm. This is the first stage of the operation of the tracker, i.e., passive tracking since it is required that the sun comes inside the field of vision of the webcam in order to start the active tracking of the sun using computer vision. To achieve this passive tracking, the control unit of the system compares the reference input with the current position of the system as it tracks the sun. It leads to the reduction in error between the reference point and the actual state resulting in the minimization of control errors within a certain limit. This step is the feedforward (open loop) control part which provides an approximated position of the sun to the second part, i.e., the negative feedback control loop part of the system to track the sun actively. Fig. 4 (Oh *et al.* 2015) shows a schematic conceptual diagram of the operating principle of the passive solar tracker employed in the project.

Although SG2/SPA is a precise way to locate the sun's position, errors in tracking the sun are inevitable due to individual or combination of various reasons like inaccurate spatiotemporal data, the time delay in processing, non-parallelism of the system with the horizontal ground, and misalignment of the mechanical unit (incorrect north/south-pointing). All these pose the limitations in the effective tracking of the sun using an open-loop control system. Such a

solar tracker is not able to detect the offset in the position which is deviated from the ideal trajectory of the sun as described in Fig. 5. These disturbances might have already led to deviation from the actual position of the sun but undetected by the solar tracker system, which is the most patent disadvantage of the passive tracking system. Hence, this necessitates the use of feedback (closed-loop) control in order to provide the actual position of the sun in real-time tracking, in other words, to track the sun actively (Oh *et al.* 2015).

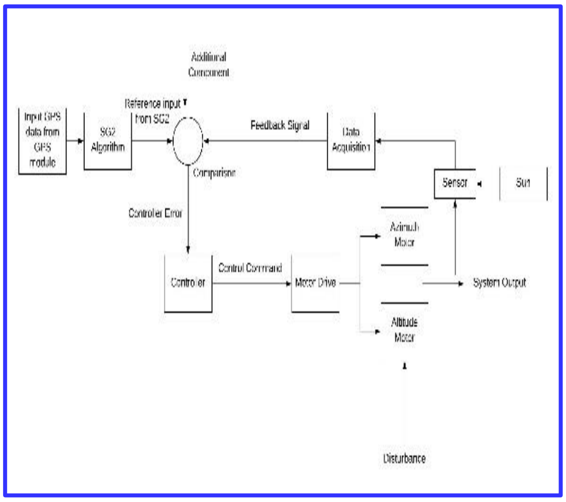

Fig. 4: Operating principle of the open-loop feed-forward control system

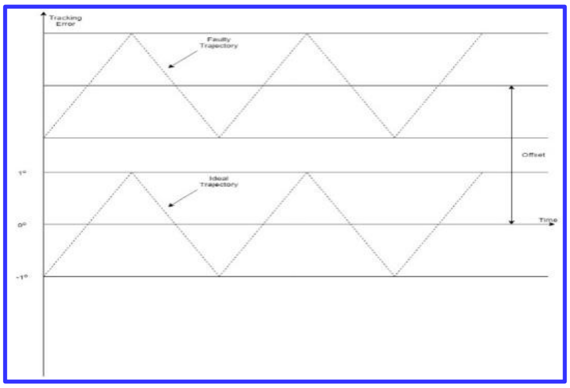

Fig. 5: Faulty trajectory at an offset from the ideal trajectory due to disturbances in the system

Thus, the negative feedback (closed-loop) control system is provided, which employs the technology of computer vision and image processing techniques. In the closed-loop mode, the feedback device, control unit, and data acquisition webcam are required to form a closed cycle (loop). Although light-dependent resistor (LDR) sensors are the most widely used in the implementation of the negative feedback control algorithm, the authors have employed computer vision as an alternative to these. It is worth mentioning that the open-loop part is not executed at all times but repeated after a defined time gap to ensure consistency in the results from the passive and active tracking and to report if any discrepancy is found. The consistency limit is defined as $\pm 1^{o}$ for the difference in passives and active tracking results.

3. ELECTRONIC CIRCUIT AND COMPUTER PROGRAMMING

3.1 Electronic Circuits

The mechanism for controlling the electro-mechanical displacement consists of two 5 volt-servo motors, one each for altitude and azimuth movements, and an electronic circuit that contains the Arduino Uno board, which works on an operating voltage of a low 5V. Uno is a microcontroller board based on the ATmega328P and is connected to the computer to control the movements of the system. The GPS module and servo motors are connected to the Uno, which drives them also provides them with a suitable working current and voltage; the motors can also be supplied with an external DC power supply. The electronic circuit performs two distinct functions, namely:

(i) The flow of data/information collected from the Data acquisition unit to the computer program (GPS module) through a USB port

(ii) The flow of the movement orders from the computer program to the servo motors.

3.2 Computer Programming

The computer program consists of the following main components:

(i) The interfacing between the computer and the electronic circuit.

(ii) Image capture of the sun and its subsequent transmission to the computer for further analysis and processing.

(iii) The error computation in the captured and actual position and thus controlling the two azimuth and altitude motors.

The image-based sensor used to identify the position of the sun provides an image including the sun, other objects, and unavoidable disturbances or noises. It is difficult to obtain a pure and clear image of the sun. Hence, to construct a high accuracy solar tracker system, the captured images must be rid of non-sun images and dealt with the noises with only a clear sun image to be displayed. Thus, image processing algorithms are used to process, analyze and identify the sun images in the picture. An image processor was proposed in the research that can sufficiently detect sun images and eliminate any possible noise on the acquired digital picture, as well as accurately find the center of the sun. A webcam and an electronic circuit are used to input the data to the computer. The color of an object in a digital photo is the combination of Red-Green-Blue (RGB) color elements (Lee *et al.* 2013). The webcam

captures the image of the sun after a fixed period of time. As already mentioned, this image is pre-binarized due to the use of a polarized filter. This captured image undergoes processing steps such as enhancing True color composite with contrast stretch, creating grayscale images for each of RGB components, a thresholding step for their binarization, and finally concatenation via an AND (&) operation, see Fig. 6 (a). This image is then cleaned by removing small objects and noises other than the sun and filling in the holes present in the image. The coordinates of the centroid of the sun, S(x,y), and the radius are calculated Fig. 6(b). The entire process of this image processing tracking approach is schematically shown in Fig. 7.

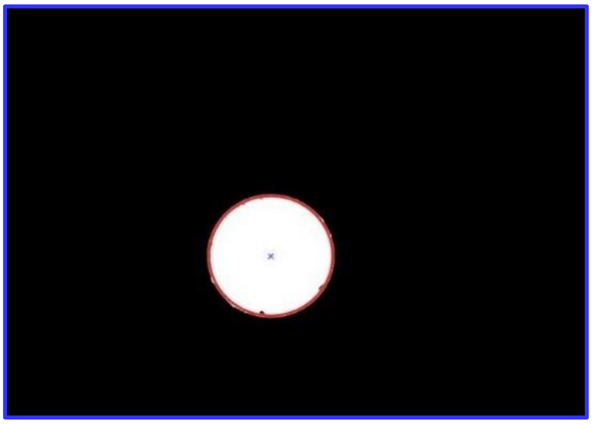

Fig. 6(a): The final binarized image after the AND (&) operation and boundary detection.

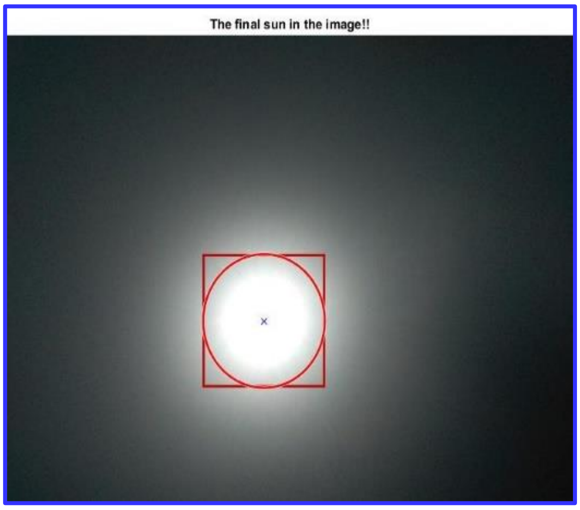

Fig. 6(b): The detection capability of the image processing algorithm

Once the centroid of the sun S(x,y) is calculated, the program forces this centroid to match with the centroid of the image C(x,y) or a point pre-defined by the user U(x,y). The above is achieved by sending appropriate control commands to the drive motors (negative feedback). This process is repeated each time the webcam captures a new image. The results of the image processing algorithm have been shown in Fig. 7 for a captured image of the sun.

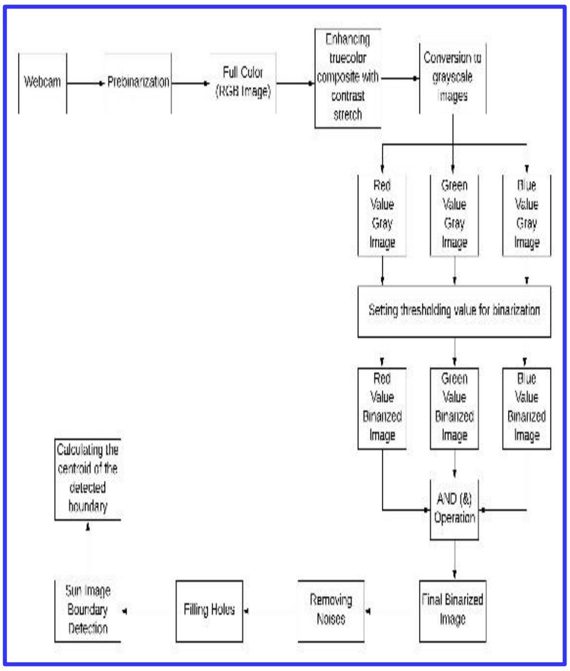

Fig. 7: The image processing scheme used in the tracking algorithm

3.3 The passive vs. active trade-off

The proposed methodology involves the use of both passive and active tracking strategies. The passive strategies are first initially used to locate and bring the sun into the field of vision of the webcam. Once this is done, the active tracking starts. However, there may be cases when the sun is not completely visible to cloudy weather conditions. In the case of partial visibility, the algorithm automatically detects the centroid of the partial region, but if the sun is completely invisible, the computer vision program fails to locate the track. Thus, in such cases, the passive tracking part again comes into play and is now used to track the sun until the computer vision program is able to track the sun actively. To ensure this trade-off works out, the results of both active and passive tracking are checked after a fixed period of time. The complete solar tracking process is shown schematically in Fig. 8.

4. COMPARISONS & CONCLUSIONS

In this work, a hybrid active-passive dual-axis solar tracking system has been proposed that is based on passive sun tracking algorithm SPA and activity tracking based on computer vision techniques. The model combines the flexibility and characteristics of both genres of tracking systems and serves to overcome the shortcomings of both types of systems. The tracker is based on simple yet effective principles of forward (open loop) and feedback (closed-loop) control systems and is quite easy to

understand in comparison to the complex methodologies adopted, as referred to in the earlier sections. The proposed method is more reliable than conventional active trackers as they often fail in case the sun is not clearly visible. In addition to the above, they also improve on the shortcomings of passive trackers that usually have significant errors in their tracking due to external disturbances.

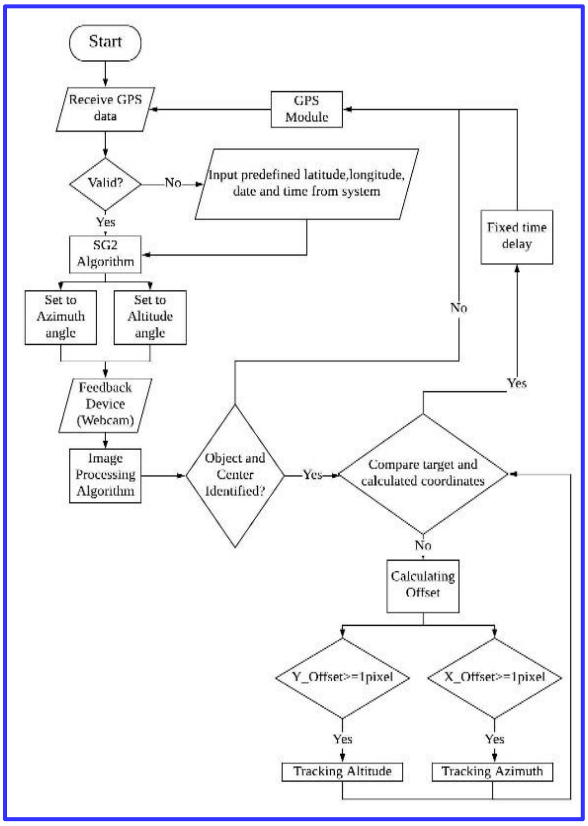

Fig. 8: The complete hybrid active-passive solar tracking algorithm

The use of a commercial webcam as a sensor allowed us to overcome the common difficulties faced by the current solar trackers in use. These being the high sensitivity of the discrete sensing elements such as photodiodes, LDR's or phototransistors to weather conditions, mainly to temperature and humidity, fast damage to these discrete elements, and the cost and maintenance of the same. One of the most important aspects of the presented controlling system is the self-adjustment and the tracking of the sun even in cloudy conditions.

The straightforward computer-lead system proposed in this work may be employed at various locations, such as to regulate the photovoltaic cells in a solar farm, terraces. With the introduction to minor adjustments, the proposed system can be used with different types of solar collector systems such as flat-plate collectors, compound parabolic collectors, parabolic trough/dish reflectors, evacuated tubes, Fresnel lens, and heliostat field collectors. The system can also be generalized to track other electromagnetic radiations of different frequencies. Of course, a special camera for picture processing is required.

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